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Bone Conduction Thresholds and Skull Vibration Measured on the Teeth during Stimulation at Different Sites on the Human Head

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Key Words
Bone conduction threshold · Cerebrospinal fluid · Conductive hearing · Head · Human · Skull bone · Stimulation · Vibration

Abstract
Vibratory auditory stimulation or bone conduction (BC) reaches the inner ear through both osseous and non-osseous structures of the head, but the contribution of the different pathways of BC is still unclear. In this study, BC thresholds in response to stimulation at several different locations including the eye were assessed, while the magnitudes of skull bone vibrations were measured on the front teeth in human subjects with either normal hearing on both sides or unilateral deafness with normal hearing on the other side. The BC thresholds with stimulation at the ipsilateral mastoid and ipsilateral temporal region were lower than the BC thresholds with stimulation at the other sites, as reported by previous works. The lower thresholds with stimulation at the ipsilateral mastoid and ipsilateral temporal region matched higher amplitudes of skull bone vibrations measured on the teeth, but only at frequencies below 1 kHz. With stimulation at the eye, the thresholds were significantly higher than those with stimulation at the bony sites in the frequency range of 0.25–4 kHz. While skull bone vibrations as measured on the teeth during stimulation at the eye were low for low frequencies, significant bone vibrations were measured at 3 and 4 kHz, indicating different pathways for BC for either the soft tissue or bony site stimulation. This finding contradicts a straightforward relationship between vibrations of the skull bones and BC hearing thresholds.

Introduction

The measurement of bone conduction (BC) thresholds is commonly used together with air conduction (AC) thresholds in clinical audiometry to differentiate conductive loss from sensorineural hearing loss. Even though such measurements have been taken for many decades, the exact routes of how the sound reaches the cochlea by BC are still unclear. Pathways of sound through osseous parts of the head have been well documented [Von Bekesy, 1932; Barany, 1938; Wever and Lawrence, 1954; Tonndorf, 1966; Stenfelt, 2005], but recent work [Sohmer et al., 2000; Freeman et al., 2000; Sohmer and Freeman, 2004; Watanabe et al., 2008] has revealed that non-osseous head contents such as the cerebrospinal fluid (CSF)

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also contribute to the sound transmission in BC. Very little is known about the frequency-specific contribution of these different pathways to the hearing sensation evoked by classical measurements of clinical BC.

BC with stimulation of the osseous parts of the head has been investigated more extensively than BC with stimulation of the soft tissue without underlying bone, such as the orbit. Measurements by Sohmer et al. [2000] pointed to a role of the dimensions of the bone. These authors obtained significantly lower BC thresholds with stimulation at the temporal region containing a thin part of the skull bone than with stimulation at the forehead containing a thicker part of the skull bone. Similar findings were also shown in the work by Dunlap et al. [1988] for dried cadaver heads, in the work by Stenfelt et al. [2005] for heads from cadavers, and in the work by Durrant and Hyre [1993] for live subjects with normal hearing. Richter and Brinkmann [1981] showed that BC thresholds with stimulation at the ipsilateral mastoid were lower than BC thresholds with stimulation at the forehead for the conventional audiometric test frequency range.

Vibratory stimulation of non-osseous parts of the head, such as the fontanelle or the eye, also leads to activation of the cochlea. Sohmer et al. [2000] recorded auditory brain stem responses with stimulation of the fontanelle in newborns where no bone was present. Watanabe et al. [2008] obtained distortion-product otoacoustic emissions by delivering f2 via a vibrator on the eye and f1 via AC. The vibratory stimuli applied to the fontanelle or the eye are presumed to communicate between the non-osseous head contents and the perilymphatic fluid through the CSF in the internal auditory meatus and the two aqueducts. Freeman et al. [2000] showed that a reduction in CSF volume resulted in elevation of BC threshold. Nakaya [2005] found a low-frequency hearing loss with low CSF pressure. Minor et al. [1998], describing patients with a dehiscence of the superior semicircular canal, showed an air-bone gap on the audiogram, particularly at frequencies below 2 kHz, without an actual conductive hearing loss [Mikulec et al., 2004; Schmuziger et al., 2006]. Rosowski et al. [2004] also showed that superior semicircular dehiscence affected hearing by BC. The assumption was that stimulation of the non-osseous parts of the head was transmitted to the perilymph through the open connection of the semicircular canal, without significant vibration of the skull bone. Sohmer et al. [2000] measured very small magnitudes of skull bone vibration with low-frequency stimulation at the eye and concluded that stimulation of soft tissues of the head did not generate significant vibration of the skull bone.

There are limitations in previous measurements of BC. First, animal heads or dried heads from cadavers were used frequently. Tonndorf [1966], whose work is one of the primary sources for the theory of BC, used cats for the majority of his investigations. Other animals as well as dry heads have been used in investigations reported in other literature [Sohmer et al., 2000; Freeman et al., 2000; Sohmer and Freeman, 2004]. Animal heads differ in geometry and composition from human heads, and heads from cadavers cannot reflect the properties of the live head with CSF. Second, the coupling force to fix the bone vibrator is an important issue for BC hearing thresholds. Thresholds improve as static force increases [Nilo et al., 1968; Yang et al., 1991]. Nevertheless, the handheld method or an elastic sweat band has been commonly used to couple the bone vibrator, and the force was not strictly controlled. Third, masking of the non-test ear is a requirement to achieve the measurement of BC hearing thresholds of the test ear. However, masking itself can influence thresholds. Overmasking occurs when the masker in the non-test ear crosses to the test ear and leads to increased thresholds because of unintentional masking of the test ear. Undermasking decreases thresholds because of bilateral summation. It is difficult and complex to find the appropriate level of masking. These differences in techniques and in subjects can cause discrepancies in the estimates of BC thresholds.

In this study, we measured BC thresholds as well as skull vibrations in the frequency range of 0.25–4 kHz in subjects with normal hearing (NH) and subjects with unilateral deafness (UD) and normal hearing on the other side, who did not require masking to obtain valid thresholds in the test ear of normal hearing. Vibratory stimulation was applied to different sites of the head, which included several bony parts and the eye. The results obtained at the different locations of stimulation were compared, and the relation between the BC threshold and skull bone vibration was examined. Two different coupling forces were applied by means of 2-N and 5-N headbands, and the BC thresholds obtained were compared.

Skull vibrations in this study were measured with an accelerometer coupled to the teeth. The coupling between the skull and the teeth is almost direct because no skin or soft tissue lies in the transmission pathway [Ozer et al., 2002]. According to the work by Hakansson et al. [1985], the skin attenuates acceleration level by about 20 dB. Previous works [Dahlin et al., 1973; Stenfelt and Hakansson, 1999] have also stated that BC thresholds up to 4 kHz with the vibrator applied to the teeth were comparable to those with the vibrator on the mastoid. The teeth are not close enough to the cochlea to represent vibrations of the otic capsule, but they form the only feasible way to measure the transmission of skull vibrations in normal human subjects without attenuation by skin or subcutaneous tissues.

Subjects and Methods

Subjects

Ten subjects with NH and 5 subjects with UD were tested. The NH subjects were in good health, and included 8 men and 2 women with an age range between 25 and 40 years (mean age: 31 years). The UD subjects included 4 men and 1 woman with an age range between 21 and 31 years (mean age: 25 years).

Inclusion criteria for NH subjects were AC thresholds lower than 25 dB HL at all the conventional audiometric test frequencies (0.25–8 kHz) bilaterally. The ear with the overall lower AC thresholds was selected as the test ear. For UD subjects, AC thresholds also had to be lower than 25 dB HL in the normal hearing ear and higher than 90 dB HL in the non-test ear over the audiometric frequency range. The AC threshold measurements were performed using conventional techniques with an audiometer (OBITER922DH/2, Madsen) and insert earphones (Tone 3A, EAR Auditory Systems). A conventional bracketing method was used to obtain responses with a step size of 5 dB, and participants responded by pressing a response button.

This study was approved by the Ethic Committee of the University Hospital of Zürich, and informed consent was obtained from all subjects.

Measurement of BC Threshold

Pure-tone BC audiometry was performed at the frequencies of 0.25, 0.5, 1, 2, 3, and 4 kHz using a bone vibrator (Radioear B72, Radioear Corp.) routed from a standard audiometer. The same conventional bracketing method as for the AC measurements was used. The stimulation output of the B72 was calibrated using an artificial mastoid (Type 4930, Brüel and Kjær) in advance.

BC thresholds were measured with stimulation at 6 different sites of the head: the forehead, the ipsilateral and contralateral mastoids, the ipsilateral and contralateral temporal regions, and the ipsilateral eye. The temporal region, which is called the ultrasound window in neurology [Garfin, 1986], is located above the zygomatic bone just anterior to the helix root. It is characterized by a thin bony separation to the skull with relative transparency for ultrasound waves.

The bone vibrator was fixed at the measurement sites with a static force of either 2 N or 5 N provided by steel headbands. The coupling forces were checked with a spring gauge (Light Line, Pesola*)*. The stimulation at the eye was performed only with the 2-N headband because the 5-N headband causes too much discomfort. Before the bone vibrator was placed on the eye, subjects were instructed to close their eyes. Any contact between the bone vibrator and the bony rim of the orbit was carefully avoided.

In the NH subjects, narrow-band masking of 60 dB HL with center frequencies corresponding to the pure-tone test frequency was applied to the non-test ear using an insert earphone (Tone 3A, EAR Auditory Systems). To prevent the perception of air-conducted sounds radiating from the bone vibrator, the insert earphones used for AC thresholds were left in the external auditory canals of both ears and thereby occlusion effects were induced, particularly below 2 kHz [Elpern and Naunton, 1963; Fagelson and Martin, 1994].

In an effort to reduce the occlusion effect, the earphones were inserted as deeply as possible at the beginning of the measurements and were maintained in place throughout the whole test period. Recent work [Dean and Martin, 2000] revealed that deep insertion of insert earphones resulted in lesser amounts of occlusion effects than shallow insertion or the use of supra-aural earphones. Dean and Martin also showed that the occlusion effects with deeply placed insert earphones did not vary significantly with stimulation location. Given that the comparisons for this study were relative, the effects of occluding the ear canal were considered not to be as critical as preventing air-conducted sounds from entering the ear canal.

Measurement of Skull Vibration

Vibrations of the skull bone were measured with an accelerometer (Type 4374, Brüel and Kjær), which was held by the subjects between their own natural teeth. They were instructed to bite on the accelerometer between the upper and lower incisor teeth with constant pressure. The accelerometer was covered with a plastic housing filled with packed wax, and sensitive spatial orientation was directed towards the upper incisor teeth. The correct placement of the accelerometer was visually checked repeatedly, and any contact with the upper or lower lips was carefully avoided. Subjects were trained to maintain a consistent biting force, and this was checked during several trial measurements. Continuous or objective monitoring was not carried out during the experiments.

The acceleration measured on the teeth was transduced to an electrical charge via the accelerometer, and amplified and filtered by a charge amplifier (Type 2635, Brüel and Kjær) with a high-pass filter of 20 Hz and a low-pass filter of 10 kHz. The electrical signal was visually controlled with an oscilloscope (HM203-7, Hameg), captured through the adaptor (BNC-2110, National Instruments) and a multi-function DAQ device (PCI 6052E, National Instruments), and analyzed by Lab VIEW 7.1 software (National Instruments). A sampling frequency of 100 kHz was chosen, and the frequency resolution was set at 10 Hz. Consequently, the time trace in each single measurement was 100 ms. The measurement period of 100 ms was averaged 100 times for each stimulation frequency, and reliable signal-to-noise ratios of 10–20 dB could be obtained. The total measurement time for each frequency was 10 s. The recorded data were transformed to the frequency spectrum of the root mean square values in the frequency domain by Fast Fourier Transform.

Accelerations at the teeth were measured when the bone vibrator was applied with a 5-N headband placed on the ipsilateral mastoid, ipsilateral temporal region, forehead, and with a 2-N headband on the ipsilateral eye. Continuous pure-tone stimulation was set to the voltage value corresponding to 50 dB HL as calibrated for the B72 bone vibrator applied to the mastoid at the frequencies of 0.25, 0.5, 1, 2, 3, and 4 kHz. To examine the linearity of the vibration measurements, the stimulus was also increased by 10 and 20 dB at 1 and 2 kHz.

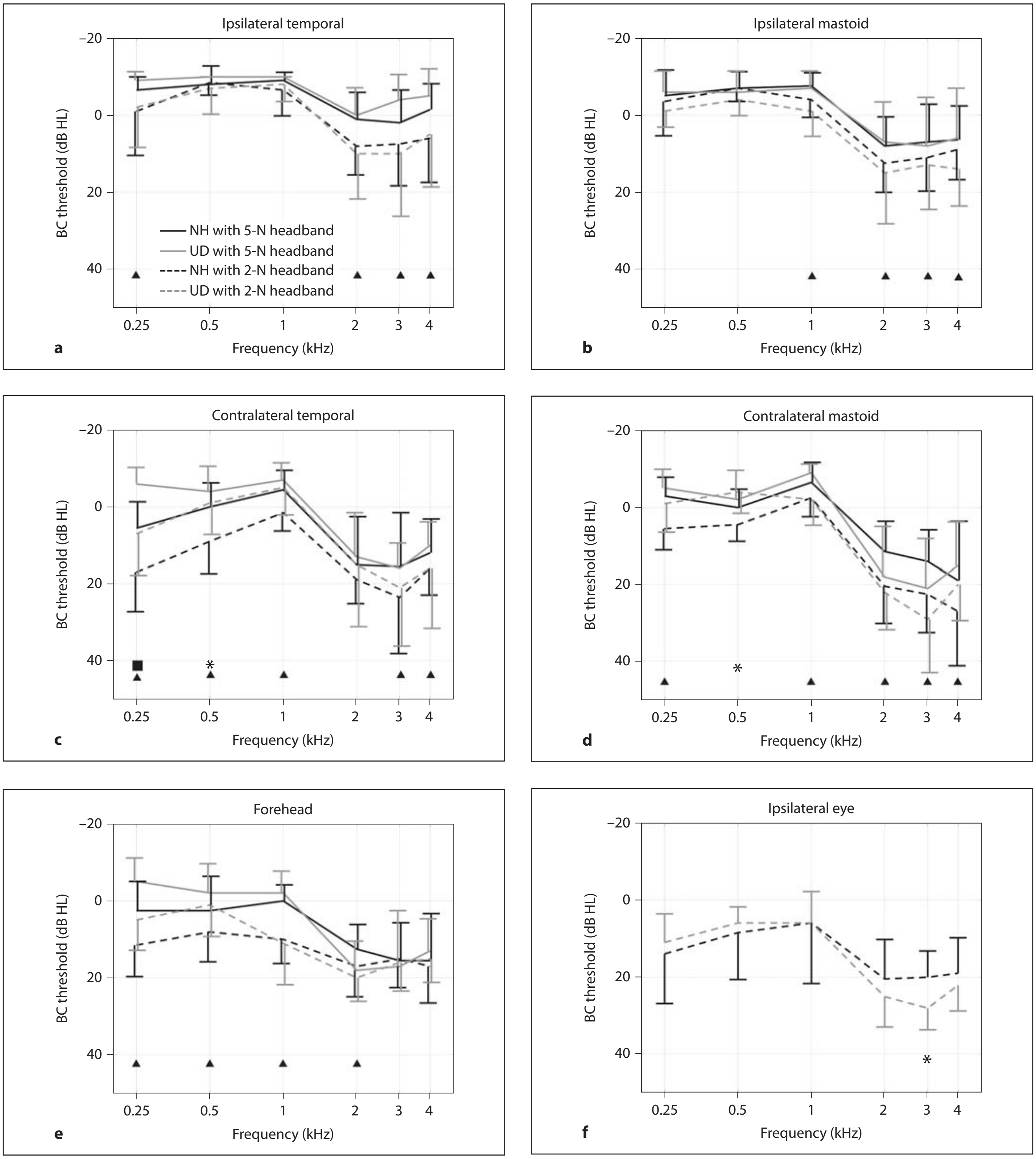

Fig. 1. Measurements of BC thresholds with the 2-N and 5-N headbands in the NH group (n = 10) and the UD group (n = 5). Stimulation at the ipsilateral temporal region (**a**), ipsilateral mastoid (**b**), contralateral temporal region (**c**), contralateral mastoid (**d**), forehead (**e**), and ipsilateral eye (**f**). The 5-N headband was not applied to stimulation at the ipsilateral eye due to safety issues. The vertical bars indicate the corresponding standard deviations. Significant differences ($p < 0.05$) are marked as * (2-N headband) and ■ (5-N headband) between NH and UD subjects, and ▲ between 2-N and 5-N headbands.

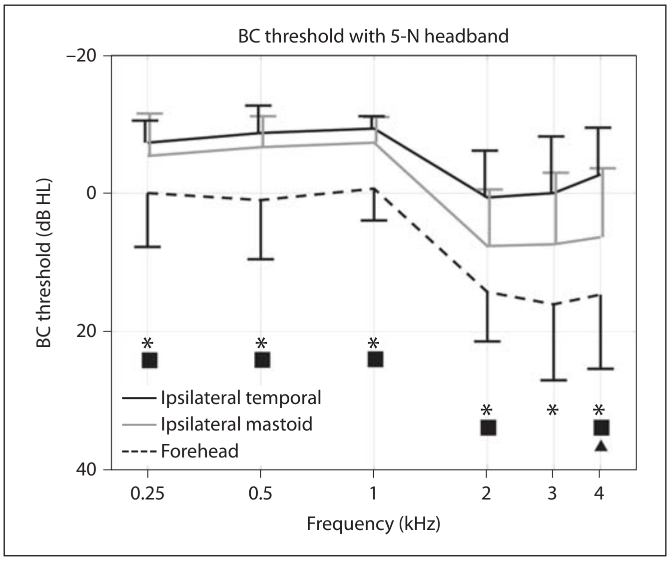

Fig. 2. Mean BC threshold for combined NH and UD subjects (n = 15) with 5-N headband for stimulation at the ipsilateral temporal region, ipsilateral mastoid, and forehead. The vertical bars indicate the corresponding standard deviations. Significant differences are marked as * between the ipsilateral temporal region and forehead, ■ between the ipsilateral mastoid and forehead, and ▲ between the ipsilateral temporal region and mastoid.

Statistical Analysis

One-way ANOVA followed by Tukey's post hoc test was used for comparison of the different stimulation sites. One-sided p values with the Wilcoxon matched-pairs signed-rank test were calculated for comparison between 2-N and 5-N coupling forces applied to the vibrator. Wilcoxon unpaired 2-sample tests were performed to determine p values between the measurements for NH and UD subjects. Statistical analyses were computed using StatMate V3 software (ATMS), and values of $p < 0.05$ were considered as significant.

Results

BC Threshold

Figure 1 illustrates BC threshold measurements in the NH and UD subjects with the 2-N and 5-N headbands, for each stimulation location. As already described, only a 2-N headband was applied to the eye.

With contralateral stimulation, the BC thresholds at 0.25 and 0.5 kHz were generally lower in the UD subjects than in the NH subjects, and some differences were significant ($p < 0.01$ with the 2-N headband at 0.5 kHz for stimulation at the contralateral mastoid; $p < 0.01$ with the 5-N headband at 0.25 kHz; $p < 0.05$ with the 2-N headband at 0.5 kHz for stimulation at the contralateral temporal region). The trend of lower thresholds in UD subjects also existed in the BC thresholds with stimulation at the forehead, but significant differences were not found. For ipsilateral stimulation, NH and UD subjects showed similar values in BC thresholds at low frequencies. At frequencies above 0.5 kHz, a significant difference between the NH and UD subjects was found only for stimulation at the eye at 3 kHz ($p < 0.05$, thresholds of NH subjects lower with 2-N headband).

The BC thresholds measured with the 5-N headband were generally lower than those with the 2-N headband for all stimulation locations across the measurement frequency range.

Figure 2 represents the mean BC thresholds for all 15 NH and UD subjects with the 5-N headband for stimulation at the ipsilateral temporal region, ipsilateral mastoid, and forehead. The ANOVA yielded F values of 6.0, 10.8, 24.5, 12.9, 9.7, and 13.0 at 0.25, 0.5, 1, 2, 3, and 4 kHz, respectively. The stimulation at the ipsilateral temporal region produced the lowest BC thresholds at all frequencies. The BC threshold with stimulation at the forehead was significantly higher than the BC threshold with stimulation at the ipsilateral temporal region ($p < 0.05$ at all frequencies) and the ipsilateral mastoid ($p < 0.05$ except for 3 kHz). The difference between the ipsilateral temporal region and the ipsilateral mastoid was small compared to the difference between the ipsilateral mastoid and forehead ($p < 0.05$ only at 4 kHz).

Figure 3 illustrates the combined mean BC thresholds for NH and UD subjects with the 2-N headband for stimulation at the ipsilateral temporal region (black solid), ipsilateral mastoid (gray solid), forehead (black dashed), and ipsilateral eye (gray dashed). The BC thresholds with stimulation at the ipsilateral eye were significantly higher than the BC thresholds with stimulation at the ipsilateral temporal region ($p < 0.01$ at all frequencies) and ipsilateral mastoid ($p < 0.05$ at all frequencies). BC thresholds were similar for stimulation at the ipsilateral eye and forehead, and there were no significant differences between them.

Figure 4 displays a comparison of the combined mean BC thresholds for NH and UD subjects between ipsilateral and contralateral stimulation with the 5-N headband. The ipsilateral stimulation yielded lower BC thresholds than the contralateral stimulation. The difference between the ipsilateral and contralateral temporal regions ($p < 0.01$ at all frequencies) was generally larger than the difference between the ipsilateral and contralateral mastoids ($p < 0.01$ at 0.5, 3, and 4 kHz, and $p < 0.05$ at 2 kHz).

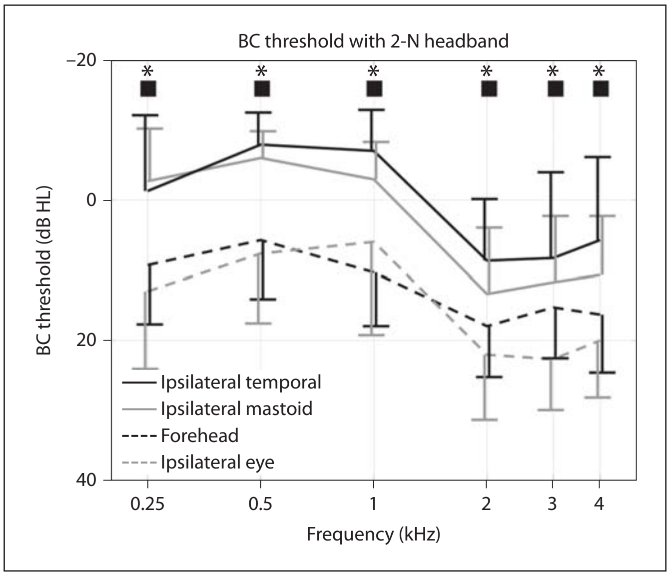

Fig. 3. Mean BC threshold for combined NH and UD subjects (n = 15) with 2-N headband for stimulation at the ipsilateral temporal region, ipsilateral mastoid, forehead, and eye. The vertical bars indicate the corresponding standard deviations. Significant differences are marked as * between the eye and ipsilateral temporal region, and ■ between the eye and ipsilateral mastoid.

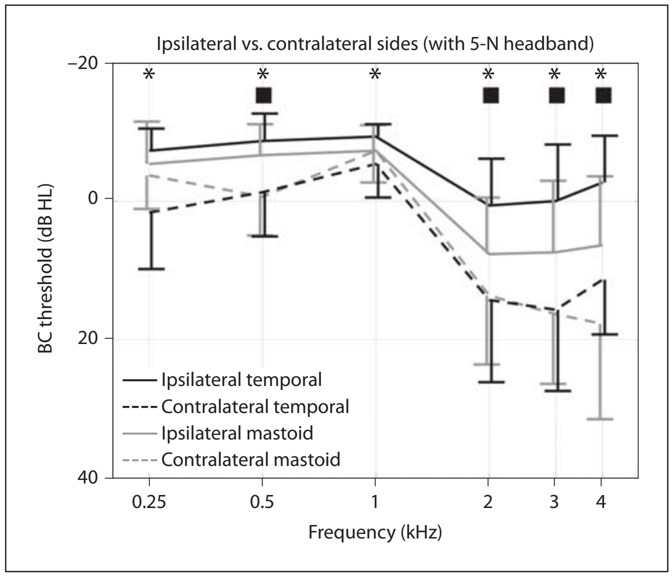

Fig. 4. Comparison of the mean BC threshold for combined NH and UD subjects between ipsilateral and contralateral stimulation with 5-N headbands (n = 15) in temporal regions and mastoids. The vertical bars indicate the corresponding standard deviations. Significant differences are marked as * between the ipsilateral and contralateral temporal regions, and ■ between the ipsilateral and contralateral mastoids.

Skull Vibration

As described in the 'Methods' section, skull vibrations were measured on the teeth when stimulation with a 5-N headband was applied to the ipsilateral mastoid, ipsilateral temporal region, and forehead. A 2-N headband was used on the ipsilateral eye.

Figure 5 displays acceleration measured at 3 levels on the teeth for stimulation at 4 different locations (black solid for temporal region, gray solid for mastoid, black dashed for forehead, and gray dashed for eye). These measurements were performed to check for linearity and also to verify the repeatability of our measurements of acceleration. Stimulations of 50, 60, and 70 dB HL at 1 kHz (fig. 5a) and 2 kHz (fig. 5b) were applied to the 4 different stimulation locations. For all 4 locations, the measured accelerations showed a linear growth with increasing magnitude of stimulating force.

Figure 6 displays the mean values of the measured accelerations for the 4 different locations of stimulation (F = 8.2, 9.4, 4.4, 1.6, 5.7, and 3.9 at 0.25, 0.5, 1, 2, 3, and 4 kHz, respectively). The mean acceleration with stimulation at the eye was significantly lower ($p < 0.05$) at 0.25 and 0.5 kHz than the mean accelerations with stimulation at all other sites. At 1 kHz, it was significantly lower only in comparison to the temporal region, and there was a significantly higher mean acceleration ($p < 0.05$) compared to the mastoid stimulation at 3 kHz. With stimulation at the mastoid, significantly lower acceleration was measured than with stimulation at the forehead at 3 ($p < 0.01$) and 4 ($p < 0.05$) kHz.

The comparison of the accelerations between the eye and bony site stimulation in figure 6 is presumed to include the effects of the different coupling forces between the actuator and stimulation sites. To compare the amounts of vibration transferred by the skull, the measured accelerations for the bony site stimulation were converted to equivalent accelerations with the 2-N headband by adding the difference in the BC thresholds between the 2-N and 5-N headbands. Figure 7 displays the ratios of acceleration with stimulation at the eye to the converted equivalent accelerations with stimulation at the bony sites. At 0.25 and 0.5 kHz, the accelerations with stimulation at the eye were lower than the accelerations with stimulation at the bony sites by approximately 20 dB ($p < 0.01$ at 0.25 and 0.5 kHz between the eye and temporal region; $p < 0.01$ at 0.25 kHz and $p < 0.05$ at

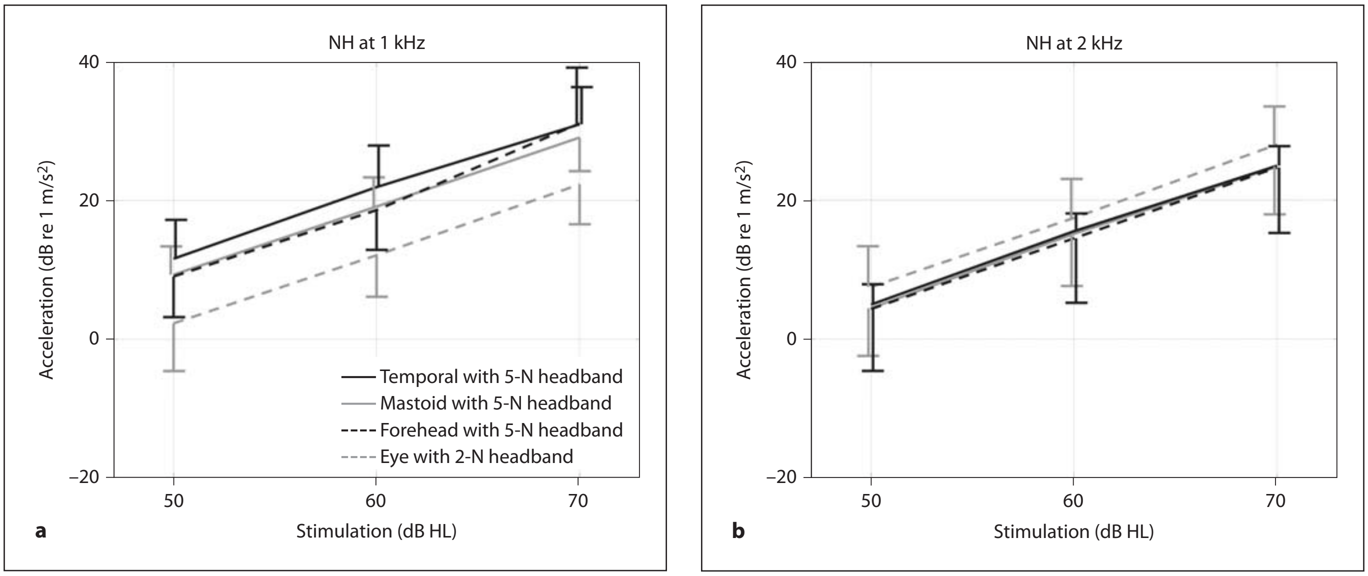

Fig. 5. Skull vibrations as measured on the teeth with different magnitudes of stimulation in the NH subjects (n = 10) at 1 kHz (**a**) and at 2 kHz (**b**). The 5-N headband was used for stimulation at the ipsilateral mastoid, ipsilateral temporal region, and the forehead, while the 2-N headband was used for stimulation at the ipsilateral eye. The vertical bars indicate the corresponding standard deviations.

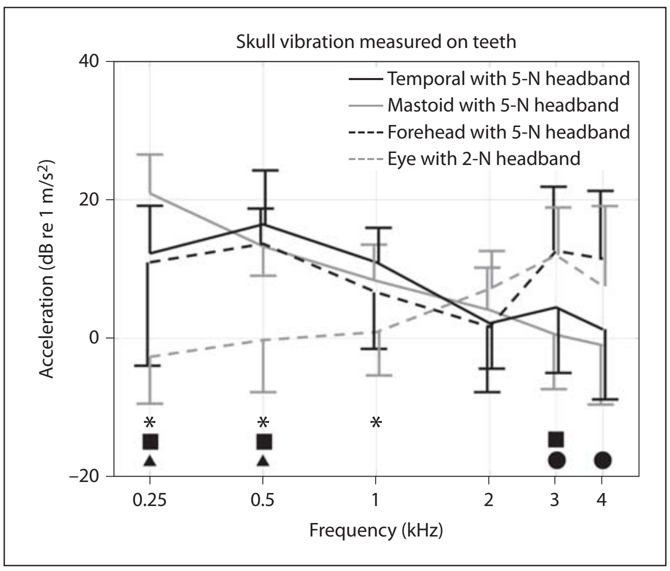

Fig. 6. Skull vibrations as measured at 50 dB HL on the teeth with different locations of stimulation (n = 15). The 5-N headband was used for stimulation at the ipsilateral mastoid, ipsilateral temporal region, and the forehead, while the 2-N headband was used for stimulation at the ipsilateral eye. The vertical bars indicate the corresponding standard deviations. Significant differences were marked as * between the temporal region and eye, ■ between the mastoid and eye, ▲ between the forehead and eye, and ● between the mastoid and forehead.

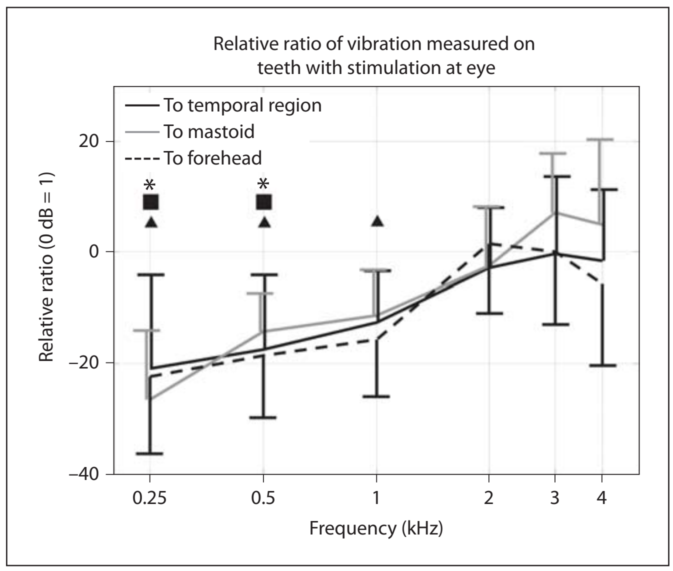

Fig. 7. Ratios of skull vibrations as measured on the teeth with stimulation at the eye versus with stimulation at the bony sites. The accelerations for the bony site stimulation with the 5-N headband were converted to equivalent accelerations with the 2-N headband by adding the difference in the BC thresholds between the 2-N and 5-N headbands to the measured accelerations with the 5-N headband. The vertical bars indicate the corresponding standard deviations. Significant differences between stimulation at the eye and bony sites were marked as * between the temporal region and eye, ■ between the mastoid and eye, and ▲ between the forehead and eye.

0.5 kHz between the eye and mastoid; $p < 0.01$ at 0.25 and 0.5 kHz and $p < 0.05$ at 1 kHz between the eye and forehead). Above 1 kHz, the accelerations with stimulation at the eye had magnitudes similar to those with stimulation at the bony sites, and no significant differences were found.

Discussion

We compared subjective BC thresholds obtained with stimulation at different sites on the human head, which includes both bone and soft tissue. Skull bone vibrations induced during stimulation at these sites were measured objectively with an accelerometer coupled to the teeth. A straightforward interpretation of our results is not possible; however, several conclusions may be drawn. While subjective BC thresholds with stimulation at the eye were higher by about 10 dB over the entire measured frequency range (fig. 3), vibrations measured on the teeth with stimulation at the eye were lower only for the low frequencies (fig. 7). This finding excludes a direct correlation between the magnitude of vibrations of the teeth and BC thresholds, and it indicates the presence of different pathways of activation of the cochlea in BC stimulation. These pathways may include the classically recognized transmission of vibrations of the otic capsule to the perilymph as well as a transmission of vibrations through the fluid connections between the CSF and the perilymph.

In addition, our comparison of the different sites of stimulation using different coupling forces and accounting for crossover between the 2 ears by including subjects with UD and normal hearing on the other side point to a possible advantage of using the temporal site rather than the mastoid for routine clinical measurements.

Subjective BC Hearing Thresholds

Significant differences in the BC thresholds between the NH and UD subjects with lower thresholds in the UD group were found at 0.5 kHz for stimulation at the contralateral mastoid and 0.25 and 0.5 kHz for stimulation at the contralateral temporal region (fig. 1). It was not the primary intention of this study to test the influence of masking using a group of subjects with UD and normal hearing on the other side, and the UD group was relatively small. Nevertheless, our findings that significant differences in BC thresholds between the NH and UD subjects (1) were only found in contralateral stimulation conditions, (2) were only found in the low frequencies, and (3) were always in favor of the UD group argue for a crossover influence of the masking noise to the test ear. No masking was necessary in UD subjects.

The coupling force needed to maintain the bone vibrator in place is considered important in BC measurement [Nilo et al., 1968; Yang et al., 1991], and coupling forces of more than 4 N are recommended for reliable BC measurements clinically. In our measurements, BC thresholds obtained with the 5-N headband were significantly lower than those made with the 2-N headband at most frequencies with stimulation at all bony sites.

Based on comparisons of the BC thresholds obtained with stimulation at the bony sites (fig. 2), both the ipsilateral temporal region and mastoid showed lower BC thresholds by about 10 dB than stimulation at the forehead. These results correspond well with the findings by Richter and Brinkmann [1981] who described a difference between BC thresholds with forehead and mastoid stimulation of >11 dB. The American National Standards Institute (ANSI) has reported that adult behavioral thresholds measured with forehead stimulation are higher than those for mastoid placement of stimulation, by 14.0, 8.5, 11.5, 8.0 dB at 0.5, 1, 2, and 4 kHz, respectively. Our results replicated these findings. BC thresholds were lower with stimulation at the temporal region than at the mastoid, although a significant difference was found only at 4 kHz.

The BC thresholds with ipsilateral stimulation were lower than those with contralateral stimulation (fig. 4). This transcranial attenuation may be explained by a decline in skull vibration with distance from stimulation [Dunlap et al., 1988; Durrant and Hyre, 1993; Sohmer et al., 2000; Stenfelt et al., 2005]. Our results agreed well with the transcranial attenuation of vibration reported by these previous works, especially for the high frequencies.

Sohmer et al. [2000] measured a decline of more than 15 dB at the inion just opposite the center of the forehead with stimulation at the forehead. The transcranial attenuation in our BC threshold measurements was smaller than that reported by Sohmer et al. [2000]. Differences between ipsilateral and contralateral temporal regions were less than 10 dB at 0.25, 0.5, and 1 kHz, and close to 15 dB above 1 kHz. The transcranial attenuation between ipsilateral and contralateral mastoids was smaller than that of the temporal regions.

Taking our results of NH subjects and subjects with UD together, the BC thresholds with stimulation at the temporal region were found to be similar to or even lower than the BC thresholds with stimulation at the mastoid for equal magnitudes of stimulation (fig. 2). Moreover, the vibrator can be placed more easily and reliably on the temporal region than on the mastoid. Thus, the temporal site should be evaluated further as an alternative to the standard clinical use of the mastoid. Our additional finding of higher transcranial attenuation for stimulation at the temporal region compared to stimulation at the mastoid (fig. 4) also supports this conclusion because more attenuation means less interference from the non-test ear with less cross-over potential between ipsilateral and contralateral sides.

Our results indicate that BC thresholds obtained with vibratory stimulation at the ipsilateral mastoid and temporal region were significantly lower than those obtained with stimulation at the ipsilateral eye across the tested frequency range (fig. 3). BC thresholds with stimulation at the eye were similar to those with stimulation at the forehead. Considering that the ipsilateral mastoid and temporal regions are closer to the tested ear than the eye or the forehead, the differences could be partially due to distance rather than non-osseous versus osseous locations of stimulation. However, distance alone is not the only factor determining the sensitivity of the BC thresholds, which becomes evident when considering the thresholds obtained with contralateral stimulation.

Skull Bone Vibration

Von Bekesy [1932] described that skull vibrations induced at the site of a bone vibrator on the skull may produce standing waves over much of the skull. When the skull vibration of the live head was measured, the skin damped the vibratory energy. Hakansson et al. [1985] noted considerable attenuation by the skin. Ideally, bone vibrations should be measured near or at the otic capsule to gain reliable information about vibrations reaching the cochlea. Obviously, such measurements are not possible in human subjects in clinical testing. Measurements closer to this site may be possible using the osseo-integrated fixture in patients fitted with bone-anchored hearing aids (BAHA), which was not the case in our subjects. Instead, we used an accelerometer coupled to the teeth to obtain a measure of bone vibrations. The teeth are known to be a good site for BC stimulation, and the absence of any soft tissue damping makes this site more sensitive to vibratory measurements than any transcutaneous sites. Stenfelt and Hakansson [1999] measured bone-conducted sound at 3 locations: percutaneous titanium implants in the temporal bone, the mastoid covered with skin, and the teeth. They showed that the teeth can be used for the application of bone-conducted sound, in particular for preoperative assessment of a BAHA and for reliable assessment of a BAHA postoperatively. Dahlin et al. [1973] also found that the teeth are reliable sites for application of vibratory audio signals because the sensitivity of a tooth does not change from point to point on its surface. In our study, vibrations of the skull bones were measured with an accelerometer coupled to the teeth. It is quite clear that this measurement does not represent the vibration of the otic capsule as transmitted to the cochlear fluids.

The measured accelerations in the NH subjects at 1 and 2 kHz showed an almost linear increase for stimulation at 50, 60 and 70 dB HL (fig. 5). Hakansson et al. [1996] also found that linearity of the BC sound transmission through the human skull was maintained up to 77 dB HL without distortion, for the frequencies 0.1–10 kHz. Our measurements were made at 50 dB HL (fig. 6), but based upon the linearity of the measurements in figure 5, it can be assumed that the results can be extended down to threshold levels of stimulation.

The accelerations were similar up to 2 kHz for all bony site stimulations, while the results were variable above 2 kHz. The accelerations with stimulation at the eye increased with frequency. They were significantly smaller than those with stimulation at the bony sites at frequencies below 1 kHz, but they were just as large above 2 kHz. Sohmer et al. [2000] described that vibratory stimulation at the eye was not significantly radiated to the surrounding bone, but they used only slowly varying stimulation with respect to time and did not measure acceleration as a function of frequency. The fact that the eye stimulation induced low skull vibrations below 2 kHz but high vibrations above 2 kHz may be related to unique and unknown acoustic properties characterizing the transmission of the soft tissue vibration within the head to the skull bone.

Relationship between BC Hearing Thresholds and Skull Vibrations

Considering the interference of transcranial attenuation, the comparison of the measurements of BC thresholds and skull vibrations is interesting. The pattern of induced vibrations with stimulation at the eye site was clearly different from that for the other stimulation sites, where the vibrator was placed over bone. The acceleration due to eye vibration is much lower below 1 kHz than it is for skull bone vibrations with stimulation at the temporal region and mastoid, and it has equal strength above 2 kHz. If bone vibrations as measured on the teeth were related directly to cochlear stimulation, then we would expect the BC thresholds at high frequencies for stimulation at the eye to be similar to those at the temporal/mastoid sites. However, the BC thresholds with stimulation at the eye were higher, arguing for different and still unknown mechanisms in the cochlea, depending upon soft tissue or bone stimulation.

Though stimulation at the eye and forehead versus stimulation at the mastoid and temporal region resulted in higher BC thresholds across the whole measurement frequency range of 0.25–4 kHz (fig. 2, 3), they showed equal or larger strengths in accelerations measured on the teeth at frequencies above 2 kHz (fig. 6, 7). From these results, it can be concluded that bone vibrations are not directly related to BC threshold sensitivity, at least for the higher frequencies and as measured on the teeth. The low-level vibrations measured with stimulation at the eye at lower frequencies confirm that little direct transmission of the vibrator or the soft tissue orbital content to the facial bones occurred. The soft tissues of the orbital contents are connected to the skull contents through fissures and foramina, and it is likely that vibrations of the eye are transmitted through these pathways to the cochlea.

Conclusion

Our finding of high BC thresholds but large accelerations with high-frequency stimulation at the eye argues against a straightforward relationship between vibrations of the skull bones and excitation of the sensory elements within the cochlea. Rather, it indicates that there are different mechanisms and pathways for evoking cochlear excitation through stimulation of soft tissue and bone. Stimulation of soft tissue, presumably including the parts of the head containing CSF, induced primarily high-frequency skull vibrations. The low levels of bone vibrations measured objectively for the low frequencies may support the possibility of a direct excitation of the inner ear through a soft tissue and CSF pathway without significant contribution of skull bone vibrations. Precise quantification of the contribution of the two pathways of tissue vibration to sound transfer to the inner ear, namely bone vibration and sound waves through the soft tissue and fluid head contents, is not possible based upon our measurements.

In addition, our measurements point to the use of the temporal region, specifically the ultrasound window, as a site for routine placement of the vibrator for clinical BC testing. This site offers both sensitive thresholds and reliable placement of the vibrator in addition to the advantage of less cross-over from the non-test ear making the level of masking less critical.

References

Barany E: A contribution to the physiology of bone conduction. Acta Otolaryngol Suppl 1938;26:129.

Dahlin GC, Allen FG, Collard EW: Bone-conduction thresholds of human teeth. J Acoust Soc Am 1973;53:1434–1437.

Dean MS, Martin FN: Insert earphone depth and the occlusion effect. Am J Audiol 2000; 9:131–134.

Dunlap SA, Lenhardt ML, Clarke AM: Human skull vibratory patterns in audiometric and supersonic ranges. Otolaryngol Head Neck Surg 1988;99:389–391.

Durrant JD, Hyre R: Observations on temporal aspects of bone-conduction clicks: real head measurements. J Am Acad Audiol 1993;4: 213–219.

Elpern BS, Naunton RF: The stability of the occlusion effect. Arch Otolaryngol 1963;77: 376–382.

Fagelson M, Martin FN: Sound pressure in the external auditory canal during bone-conduction testing. J Am Acad Audiol 1994;5: 379–383.

Freeman S, Sichel JY, Sohmer H: Bone conduction experiments in animals – evidence for a non-osseous mechanism. Hear Res 2000; 146:72–80.

Garfin SR, Botte MJ, Waters RL, Nickel VL: Complications in the use of the halo fixation device. J Bone Joint Surg Am 1986;68:320–325.

Hakansson B, Tjellstrom A, Rosenhall U: Acceleration levels at hearing threshold with direct bone conduction versus conventional bone conduction. Acta Otolaryngol 1985; 100:240–252.

Hakansson B, Carlsson P, Brandt A, Stenfelt S: Linearity of sound transmission through the human skull in vivo. J Acoust Soc Am 1996; 99:2239–2243.

Mikulec AA, McKenna MJ, Ramsey MJ, Rosowski JJ, Herrmann BS, Rauch SD, Curtin HD, Merchant SN: Superior semicircular canal dehiscence presenting as conductive hearing loss without vertigo. Otol Neurotol 2004;25:121–129.

Minor LB, Solomon D, Zinreich JS, Zee DS: Sound- and/or pressure-induced vertigo due to bone dehiscence of the superior semicircular canal. Arch Otolaryngol Head Neck Surg 1998;124:249–258.

Nakaya M, Morita I, Horiuchi M: Recurrent hearing loss after myelography treated with epidural blood patch. Auris Nasus Larynx 2005;32:399–401.

Nilo ER: The relation of vibrator surface area and static application force to the vibrator-to-head coupling. J Speech Hear Res 1968;11: 805–810.

Ozer E, Adelman C, Freeman S, Sohmer H: Bone conduction hearing on the teeth of the lower jaw. J Basic Clin Physiol Pharmacol 2002;13: 89–96.

Richter U, Brinkmann K: Threshold of hearing by bone conduction: a contribution to international standardization. Scand Audiol 1981;10:235–237.

Rosowski JJ, Songer JE, Nakajima HH, Brinski KM, Merchant SN: Clinical, experimental, and theoretical investigations of the effect of superior semicircular canal dehiscence on hearing mechanisms. Otol Neurotol 2004; 25:323–332.

Schmuziger N, Allum J, Buitrago-Tellez C, Probst R: Incapacitating hypersensitivity to one's own body sounds due to a dehiscence of bone overlying the superior semicircular canal: a case report. Eur Arch Otorhinolaryngol 2006;263:69–74.

Sohmer H, Freeman S, Geal-Dor M, Adelman C, Savion I: Bone conduction experiments in humans – a fluid pathway from bone to ear. Hear Res 2000;146:81–88.

Sohmer H, Freeman S: Further evidence for a fluid pathway during bone conduction auditory stimulation. Hear Res 2004;193:105–110.

Stenfelt SP, Hakansson BE: Sensitivity to bone-conducted sound: excitation of the mastoid vs the teeth. Scand Audiol 1999;28:190–198.

Stenfelt S, Goode RL: Transmission properties of bone conducted sound: measurements in cadaver heads. J Acoust Soc Am 2005;118: 2373–2391.

Tonndorf J: Bone conduction. Studies in experimental animals. Acta Otolaryngol 1966;Suppl 213:1+.

Von Bekesy G: Zur Theorie des Hörens bei Schallaufnahme durch Knochenleitung. Ann Physik 1932;13:113–136.

Watanabe T, Bertoli S, Probst R: Transmission pathways of vibratory stimulation as measured by subjective thresholds and distortion-product otoacoustic emissions. Ear Hear 2008;29:667–673.

Wever EG, Lawrence M: Physiological Acoustics. Princeton University Press, 1954.

Yang EY, Stuart A, Stenstrom R, Hollet S: Effect of vibrator to head coupling force on the auditory brain stem response to bone conducted clicks in newborn infants. Ear Hear 1991; 12:55–60.